

Stream acidification and mortality of brook trout (*Salvelinus fontinalis*) in response to timber harvest in Catskill Mountain watersheds, New York, USA

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Abstract: Effects of clear-cut and timber-stand improvement (TSI) harvests on water chemistry and mortality of caged brook trout (*Salvelinus fontinalis*) were evaluated in a study of three Catskill Mountain streams, 1994–2000. Harvests removed 73% of tree basal area (BA) from a clearcut subbasin, 5% BA from a TSI subbasin, and 14% BA at a site below the confluence of both streams. A fourth nonharvested site served as a control. Water quality and trout mortality were affected only in the clearcut stream. Acidity and concentrations of nitrate and inorganic monomeric aluminum (Al_{im}) increased sharply during high flows after the first growing season (fall 1997). Acid- Al_{im} episodes were severe during this period and decreased steadily in magnitude and duration thereafter. All trout at this site died within 7 days during spring 1998 and 85% died during spring 1999. Only background mortality was observed in other years at this site and at the other three sites during all tests. The absence of mortality in TSI watersheds indicates that limited harvests should not harm brook trout populations in acid-sensitive streams. Effects of tree harvests on fish communities are of concern, however, because many stream-dwelling species are more sensitive to acidified waters than brook trout.

Résumé : Nous avons étudié en 1994–2000 les effets de la coupe à blanc et des opérations d'amélioration forestière (TSI, « timber-stand improvement ») sur la chimie de l'eau et la mortalité d'ombles de fontaine (*Salvelinus fontinalis*) encagés dans trois cours d'eau des Catskills. Les coupes forestières ont retiré 73 % de la surface terrière (BA) des arbres dans un sous-bassin soumis à la coupe à blanc, 5 % de BA dans un sous-bassin TSI et 14 % de BA dans un site situé en aval de la confluence des deux cours d'eau. Un quatrième site sans coupe a servi de témoin. La qualité de l'eau et la mortalité des ombles n'ont été affectées que dans le cours d'eau du bassin soumis à la coupe à blanc. L'acidité et les concentrations de nitrates et d'aluminium inorganique monomère (Al_{im}) ont augmenté rapidement durant les périodes de crue après la première saison de croissance (automne 1997). Les épisodes d'acidité- Al_{im} ont été intenses durant cette période pour ensuite diminuer en force et en importance par après. Tous les ombles de ce site sont morts en sept jours au printemps 1998 et 85 % sont morts au printemps 1999. Les autres années, à ce site, il n'y avait qu'une mortalité de base, comme c'était le cas aux autres trois sites durant tous les tests. L'absence de mortalité dans les bassins versants TSI indique que des coupes restreintes ne devraient pas nuire aux populations d'ombles de fontaine dans les cours d'eau sensibles à l'acidité. Les effets de la coupe des arbres sur les communautés de poissons restent préoccupants, car beaucoup d'espèces lotiques de poissons sont plus sensibles aux eaux acidifiées que ne l'est l'omble de fontaine.

[Traduit par la Rédaction]

Introduction

Stream acidification, caused by acid deposition, was first documented in New York State during the 1970s (Colquhoun et al. 1981). The adverse effects of acid deposition on water quality, fish survival, and fish populations were reported in other parts of the northeast but were most acute in lakes of the Adirondack Mountains of northern New York (Haines and Baker 1986; Baker and Gallagher 1990; Baker

et al. 1993). The only large river in the Catskill Mountains of southeastern New York with moderately to severely acidified reaches was the Neversink River (Colquhoun et al. 1981). Recent studies in the Neversink have documented brook trout (*Salvelinus fontinalis*) mortality in response to episodic and chronic stream acidification (Van Sickle et al. 1996; Baldigo and Murdoch 1997) and the spatial extent of negative effects on fish communities (Baldigo and Lawrence 2000).

A variety of forest harvest practices have also been shown to affect the chemical quality of soil and stream waters in the northeastern United States (Likens et al. 1970; Dahlgren and Driscoll 1994; Burns et al. 1997), but the effects of tree harvesting on fish survival (or mortality) and resident fish populations in acid-sensitive streams have not been well documented. Forest harvests can alter the rates of biogeochemical processes in soils and affect the chemistry of soil, ground, and surface waters for a few years to several

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decades (Likens et al. 1970; Swank and Waide 1988; Dahlgren and Driscoll 1994). Clear-cutting has been found to increase the rates of nitrate (NO_3^-) leaching from soils through increased N mineralization and nitrification and (or) decreased N uptake by vegetation, which can increase surface water concentrations of NO_3^- by more than an order of magnitude (Likens et al. 1970; Vitousek 1981; Burns et al. 1997). Characterizing the effects of forest harvest on stream water quality is problematic owing to the complexity of the N cycle, which responds simultaneously to cyclic or random variations in atmospheric deposition of nitrous oxides, soil freezing, air temperature, and defoliation of vegetation by insects (Mitchell et al. 1996; Murdoch et al. 1998).

The N cycle in the Catskill Mountain region is especially sensitive to disturbance because high rates of atmospheric N deposition (about $10\text{--}12\text{ kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) have induced a condition of N saturation whereby N retention and utilization capacity of the vegetation and microbial communities are exceeded, yielding net N surpluses and elevated concentrations of NO_3^- in shallow soil and surface waters (Murdoch and Stoddard 1992, 1993). Increased NO_3^- concentrations can increase acidity (lower pH), which in turn can increase the concentrations of total monomeric aluminum (Al_{im}) and inorganic monomeric aluminum (Al_{im}) in surface waters (Driscoll 1985). A decrease in stream pH to below 5.5 can cause concentrations of Al_{im} to exceed levels that are acutely toxic to brook trout and many other fish species (Baker et al. 1990; Baker and Christensen 1991; Baldigo and Murdoch 1997).

In 1992, the New York City Department of Environmental Protection and the US Geological Survey began a 7-year forest harvest study (Burns et al. 1997) to document the effects of clear-cut and timber-stand improvement (TSI) forest harvest practices on soil nitrification and N mineralization rates, soil- and surface-water chemistry, and brook trout mortality. Tree harvests were conducted in two adjacent subbasins of one headwater stream and chemistry and trout mortality were monitored at both streams, at a third site just below their confluence, and at a fourth site in an adjacent undisturbed (reference) subbasin. The clear-cut harvest (winter of 1996–1997) decreased tree basal area (BA) in that subbasin by 73%, and the partial TSI harvest (winter of 1995–1996 and fall of 1996) decreased tree BA in the adjacent subbasin by 5%. The result was a 14% decrease in tree BA in the combined watershed of the third site located at the confluence of the other two streams. The study investigated hypotheses that (i) decreased uptake of N, and the attendant increase in rates of nitrification and N mineralization, would produce significant increases in NO_3^- concentrations in the soil and stream waters of harvested watersheds, (ii) increased soil acidity would increase Al_{im} mobilization and increase Al_{im} concentrations in streams of harvested watersheds, and (iii) concentrations of Al_{im} in both streams would exceed levels that are acutely toxic to brook trout after the trees were harvested. This paper summarizes the water quality changes observed at streams within clear-cut, partially harvested (TSI), and reference watersheds and associated effects on brook trout mortality in each stream during 30-day exposures in the spring of each year from 1995 to 2000.

Materials and methods

Study area

The study was conducted in small watersheds draining into the West Branch Neversink River in the Catskill Mountains, southeastern New York (Fig. 1). Three of the four monitoring sites are in the Shelter Creek basin: the Dry Creek clearcut site (dc57), which is a tributary to Shelter Creek with a drainage area of 24 ha, the upper Shelter Creek TSI site (sc40) with a drainage area of 109 ha, and the lower Shelter Creek confluence site (sc20), immediately downstream of where Dry Creek joins Shelter Creek, with a drainage area of 161 ha. The reference stream site (cl25) is in an adjacent basin to the southwest (Fig. 1) and has a drainage area of 48 ha. Elevations at the monitoring stations range from about 650 to 880 m.

The Catskill Mountains consist of an uplifted plateau of Devonian sedimentary rock that has been eroded and dissected by streams and then overlain by till of varying thickness from the most recent glaciation of North America about 1000 years ago (Rich 1934; Buttner 1977). The soil is an Inceptisol and classified in the Arnot–Oquaga–Lackawana series (Tornes 1979) as a bouldery silt loam with shallow organic horizons (1.5–8 cm).

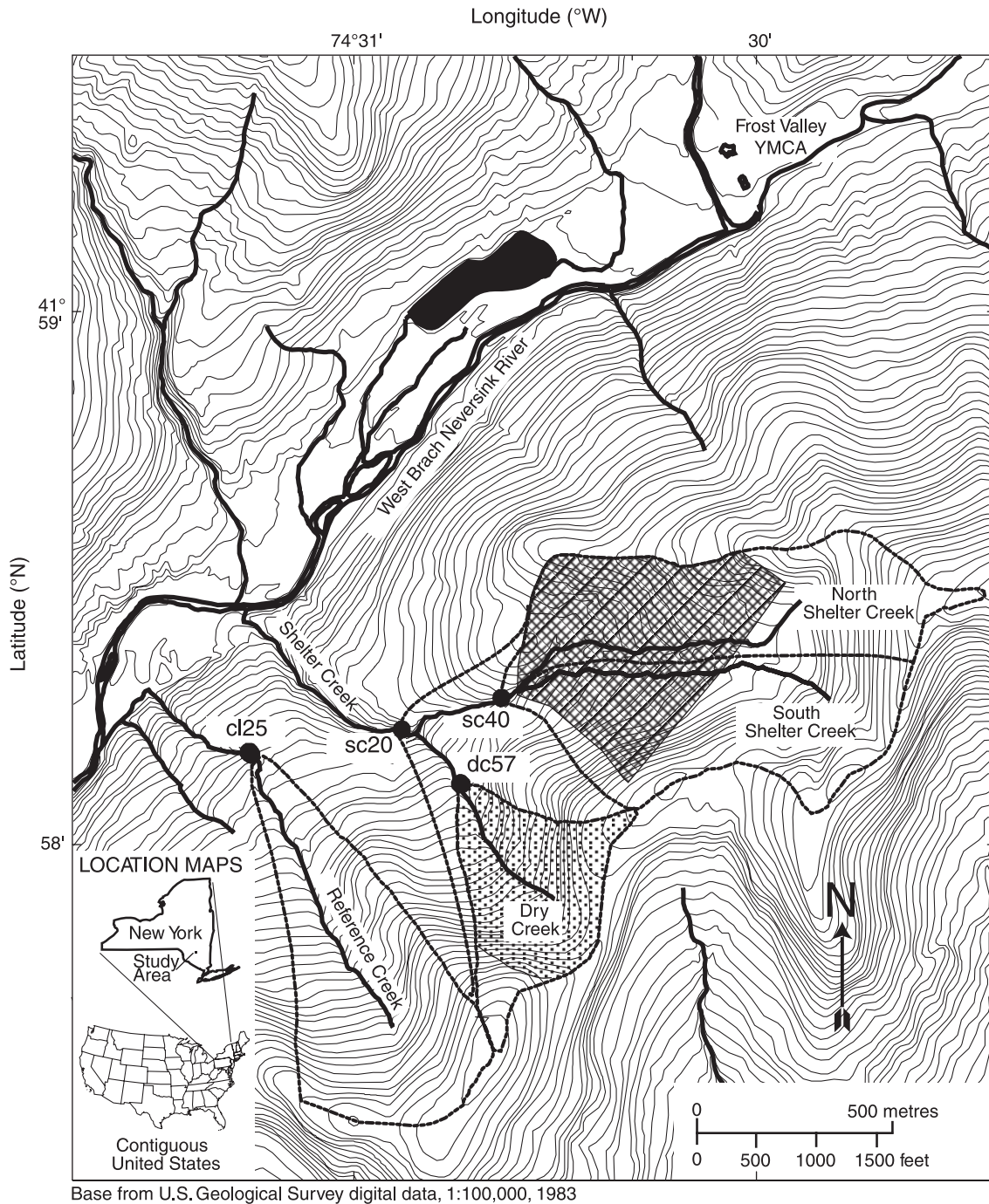
The principal land cover in the study area is mainly mixed-hardwood forest dominated by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*). Small stands of eastern hemlock (*Tsuga canadensis*) also occupy parts of the lower reference stream basin and upper Shelter Creek subbasin, but only a few isolated hemlock trees are evident in the Dry Creek subbasin.

The climate in the study area is classified as humid continental, with cold winters and moderately warm summers. The mean annual temperature at the Slide Mountain weather station (about 5 km east of the study area, 808 m elevation) was $4.6\text{ }^{\circ}\text{C}$ from 1961 to 1990 (National Oceanic and Atmospheric Administration 1990); mean annual precipitation at the same station was 134 cm from 1984 through 2001 (<http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=NY68>, accessed 1 December 2002). About 20%–25% of precipitation falls as snow. Precipitation amounts are fairly uniformly distributed throughout the year, but 32% of the Neversink River annual runoff (0.97 m) normally occurs during the snowmelt period of March and April and 28% of the annual runoff occurs during the summer months of May–September (Firda et al. 1995).

Timber harvests

Two timber harvests were completed between December 1995 and March 1997. During each harvest, slash (tree branches and tops) was left on the ground and some branches were arranged perpendicular to temporary skidding roads to form a “corduroy” surface and helped minimize physical disturbance of the forest floor. About 23% of the upper Shelter Creek subbasin (upstream of sc40) was partially cut for the TSI harvest between December 1995 and November 1996. The rest of the watershed is mostly within a New York State Wilderness Area where logging is prohibited. About 22% of tree BA was removed during the TSI

Fig. 1. Location of tree harvests and surface-water monitoring sites in Shelter Creek, Dry Creek, and Reference Creek subbasins in the Neversink River basin, New York. Tree harvest areas are denoted by crosshatching (clearcut) or stippling (timber-stand improvement), drainage-basin boundaries by broken lines, and stream sites by circles.



harvest, which resulted in a 5% decrease in tree BA in the upper Shelter Creek watershed upstream of sc40 (Fig. 1). About 75% of the Dry Creek watershed (upstream of dc57) was clear-cut from December 1996 through March 1997. The southwestern (upper) part of the Dry Creek subbasin is designated as wilderness and therefore was not harvested. The clear-cut removed about 97% of the trees in the harvested part of the Dry Creek subbasin and decreased tree BA

in the watershed upstream from dc57 by about 73%. The harvests in both the Dry Creek and upper Shelter Creek subbasins decreased tree BA in the watershed upstream from sc20 by about 14%. The upper Shelter Creek and Dry Creek subbasins had respective similar tree BA (27 and $29 \text{ m}^2\cdot\text{ha}^{-1}$), total tree biomass (216 and $232 \text{ Mg}\cdot\text{ha}^{-1}$), and understory biomass (2.3 and $3.0 \text{ Mg}\cdot\text{ha}^{-1}$) before the harvests. Total tree BA ($36 \text{ m}^2\cdot\text{ha}^{-1}$) and biomass ($295 \text{ Mg}\cdot\text{ha}^{-1}$) in the reference

watershed were greater than and understory biomass ($3.1 \text{ Mg}\cdot\text{ha}^{-1}$) was comparable with levels in the two harvested subbasins.

Stream stage and discharge

Stream stage at the three Shelter Creek sites (sc40, sc20, and dc57) was measured every 15 min with a submersible pressure transducer and recorded with an electronic data logger during the study period. Discharge was measured biweekly at all four sites in accordance with standard US Geological Survey methods (Rantz 1983). The data were used to generate stage-to-discharge relation curves (discharge rating) and continuous 15-min (and hourly) discharge records for the three Shelter Creek sites (sc40, sc20, and dc57). Fifteen-minute stage data were not logged at the reference site (cl25); therefore, biweekly discharge measurements made at cl25 and sc20 on the same dates were used to generate a model that predicts flow at cl25 from the flow at sc20. The flow model and continuous flow records from sc20 were used to estimate hourly discharge data for the reference site (cl25).

Stream chemistry

Stream water samples were collected by hand weekly or biweekly at all four stream sites from April 1993 through September 2000 for chemical analyses. The samples were collected in 500-mL polyethylene bottles and stored on ice until they could be returned to the US Geological Survey laboratory in Troy, New York. In addition, electronic data loggers were linked to stream-stage sensors only at the three Shelter Creek sites (sc40, sc20, and dc57) and were programmed to activate automated samplers to collect water samples at specified increments of rising and falling stage during storms. Storm water samples were usually returned to the laboratory within 48 h and stored at 4°C until preparation for analyses.

Most water samples were aliquoted within 2 or 7 days, depending on whether they were hand-grab or storm water samples, and analyzed for pH, acid-neutralizing capacity (ANC), sulfate (SO_4^{2-}), NO_3^- , ammonium (NH_4^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), silica (SiO_2), potassium (K^+), dissolved organic carbon (DOC), total aluminum (Al_t), Al_{im} , organic monomeric aluminum (Al_{om}), and Al_{im} at the US Geological Survey laboratory by standard methods (Lawrence et al. 1995). Data quality objectives for precision and accuracy for all analyses were 10% (coefficient of variation), and these objectives were generally met for more than 95% of the quality assurance samples (Lincoln et al. 1996).

Estimates of continuous (hourly) Al_{im} and pH data at the clearcut site and median, minimum, and maximum values for biologically important constituents at each site were assessed for each 30-day exposure period. Continuous Al_{im} and pH records at dc57 were estimated for respective exposure periods from hourly discharge data and the relationships between constituent concentrations and log-transformed discharge values. The discharge– Al_{im} relationships were significant but weak in 1997 ($R^2 = 0.13$) and 1995 ($R^2 = 0.32$) when Al_{im} concentrations stayed low. The relationships were stronger in 1996 ($R^2 = 0.78$), 1998 ($R^2 = 0.80$), 1999 ($R^2 =$

0.55), and 2000 ($R^2 = 0.76$) when Al_{im} concentrations varied more widely with stream flows. The discharge–pH relationships were stronger than discharge– Al_{im} relationships and followed similar trends; R^2 was 0.38 in 1997 and 0.52 in 1995 and ranged from 0.67 to 0.91 during the other four years. Continuous Al_{im} and pH records were not generated for the other sites where annual differences were minor and trout mortality was low or nonexistent.

Toxicity tests

Young-of-the-year brook trout (age 0+) from the New York State Department of Environmental Conservation hatchery in Rome, New York, were exposed (in cages) to stream waters at all four sites for 30-day periods during each spring from 1995 through 2000 in accordance with techniques described by Johnson et al. (1987) and Baldigo and Murdoch (1997). The exposure periods were 4 April through 5 May 1995, 2 April through 3 May 1996, 10 April through 11 May 1997, 3 April through 4 May 1998, 3 April through 3 May 1999, and 31 March through 1 May 2000. Each year, brook trout were transported from Rome to the West Branch Neversink River and placed into a large holding chamber to acclimate to local conditions for 24 h. The next day, 20 trout were placed into sixteen 4-L plastic, screen-sided jars (five trout per jar) and then transported to exposure cages at each study site (four jars and 20 trout per site). Trout were not fed during the exposure periods and mortality was checked and recorded every 2–4 days. Total length of caged trout ranged from 35 to 51 mm and averaged 43.5 mm; individual weights averaged 1.2 g. Trout lengths and weights did not differ significantly ($p \leq 0.05$) among streams or test periods.

Results and discussion

Stream stage and discharge

Daily discharge records for the four study streams, 1994–2000 (Figs. 2–5), show seasonal cycles typical of headwater streams, with the highest flows in late winter or early spring and the lowest flows in late summer or early fall. Flows at the four sites were relatively stable during all 30-day fish exposure periods, except in 1996 when two storms increased discharge at all sites by at least an order of magnitude above base flows (Fig. 6). Over the 6-year study, mean annual discharge values were $0.0046 \text{ m}^3\cdot\text{s}^{-1}$ at dc57, $0.0346 \text{ m}^3\cdot\text{s}^{-1}$ at sc40, $0.0576 \text{ m}^3\cdot\text{s}^{-1}$ at sc20, and $0.0178 \text{ m}^3\cdot\text{s}^{-1}$ at cl25. Discharge at sites dc57 and sc40 in the two harvested watersheds, on average, represented 8% and 60% of the total flow at the confluence site (sc20). Because of their semiperennial nature, steep channel slopes, and vertical barriers, resident fish communities in the four streams were limited. Although not surveyed, fish were not apparent at dc57 and sc40 and only a small number of brook trout were observed at sc20 and cl25 prior to this investigation.

Stream chemistry

Prior to tree harvests, water chemistry at all four sites was typical of acid-sensitive headwater streams in the Catskill region (Figs. 2–5). ANC levels were generally $<50 \mu\text{equiv}\cdot\text{L}^{-1}$ and occasionally negative during high flows. All four streams experienced at least one event with pH <5.0 . There-

Fig. 2. Daily discharge, acid-neutralizing capacity (ANC), pH, and concentrations of SO_4^{2-} , NO_3^- , Ca^{2+} , and inorganic monomeric aluminum (Al_{im}) for water samples from the clearcut site (dc57) in the Neversink River basin, New York, 1994–2000. The clear-cut harvest period is denoted by light stippling and the 30-day brook trout (*Salvelinus fontinalis*) exposure periods are indicated by heavy stippling.

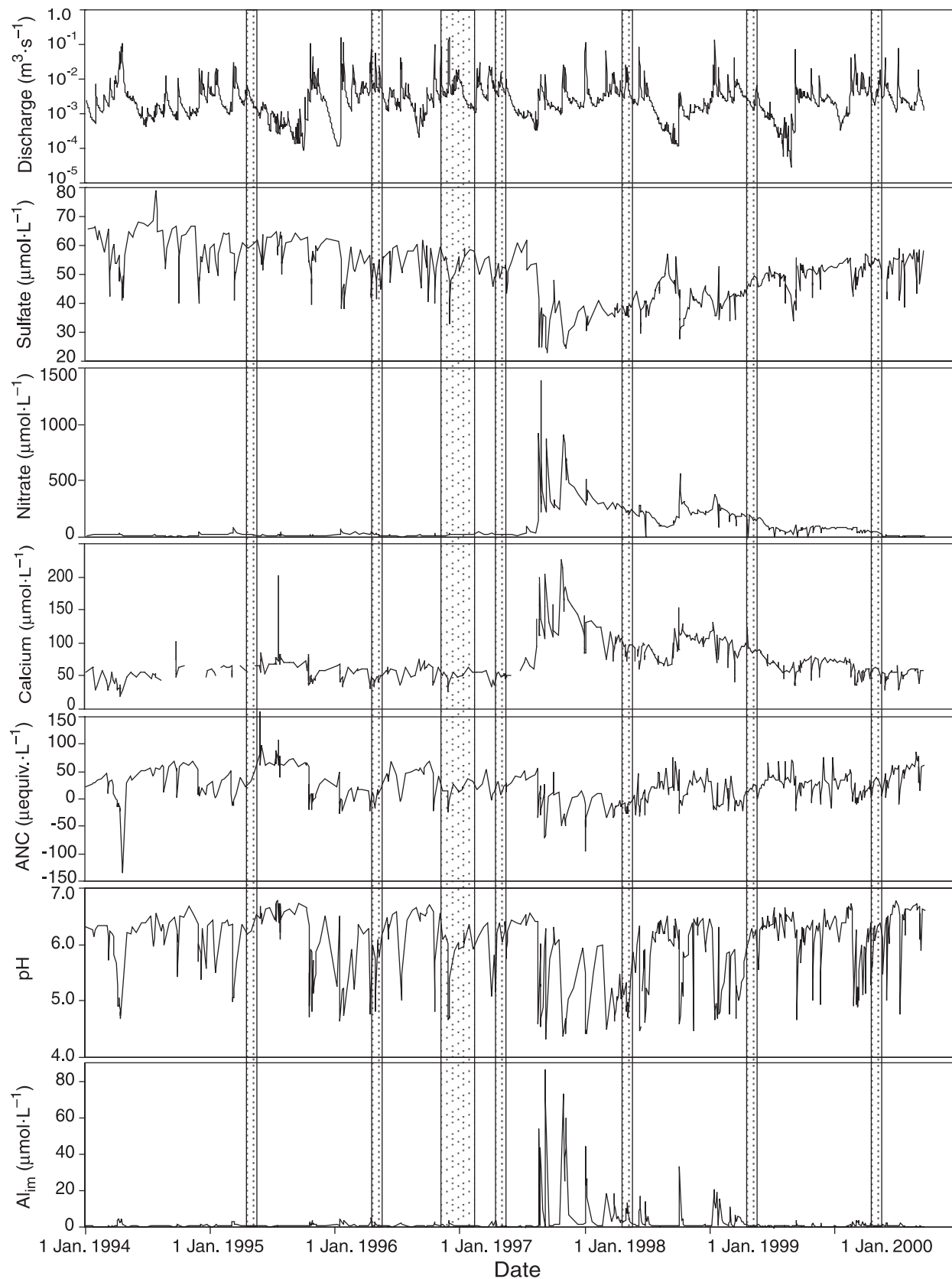


Fig. 3. Daily discharge, acid-neutralizing capacity (ANC), pH, and concentrations of SO_4^{2-} , NO_3^- , Ca^{2+} , and inorganic monomeric aluminum (Al_{im}) for water samples from the confluence site (sc20) in the Neversink River basin, New York, 1994–2000. The harvest periods in the Shelter Creek and Dry Creek subbasins are denoted by light stippling and the 30-day brook trout (*Salvelinus fontinalis*) exposure periods are indicated by heavy stippling.

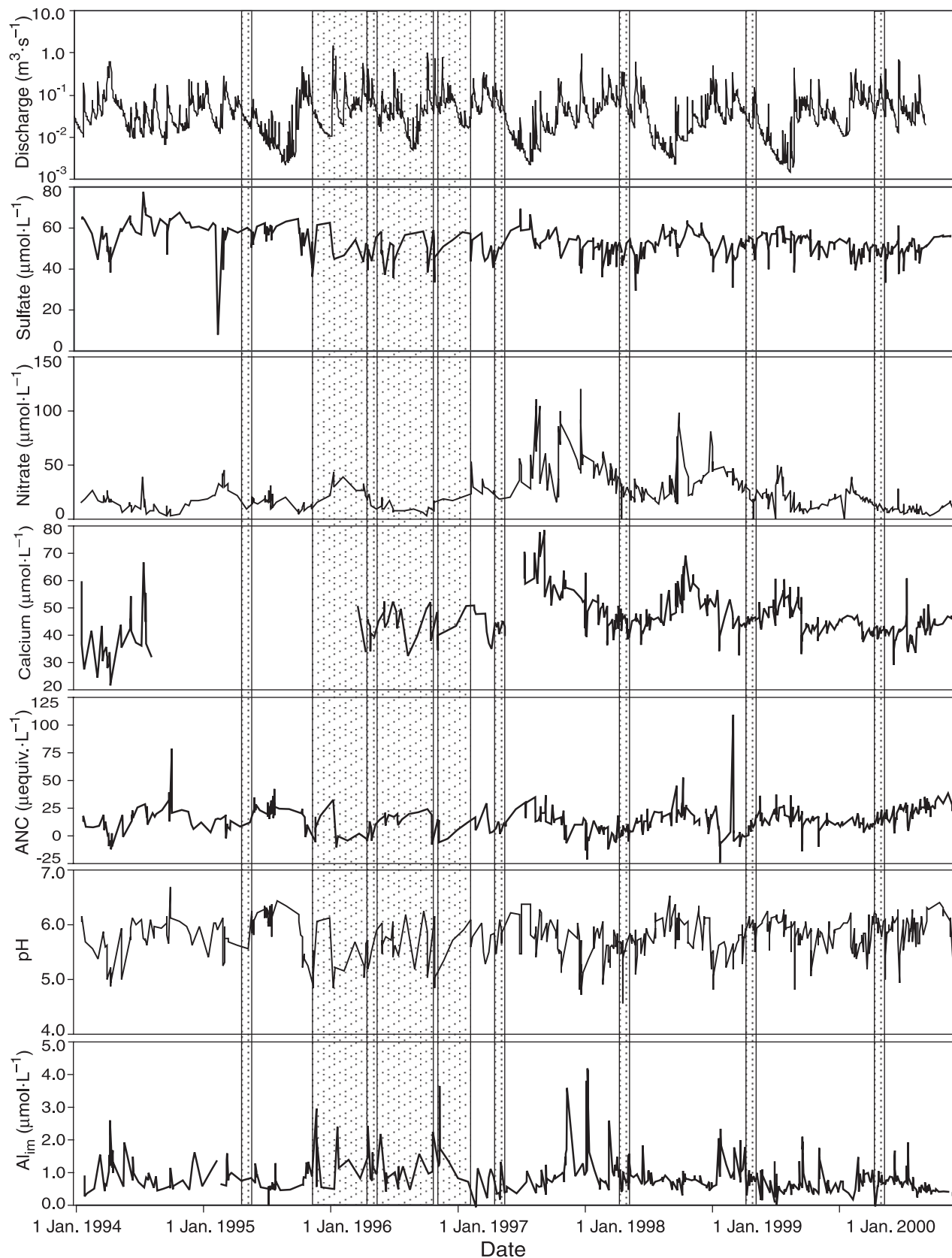


Fig. 4. Daily discharge, acid-neutralizing capacity (ANC), pH, and concentrations of SO_4^{2-} , NO_3^- , Ca^{2+} , and inorganic monomeric aluminum (Al_{im}) for water samples from the timber-stand improvement (TSI) site (sc40) in the Neversink River basin, New York, 1994–2000. The TSI harvest period is denoted by light stippling and the 30-day brook trout (*Salvelinus fontinalis*) exposure periods are indicated by heavy stippling.

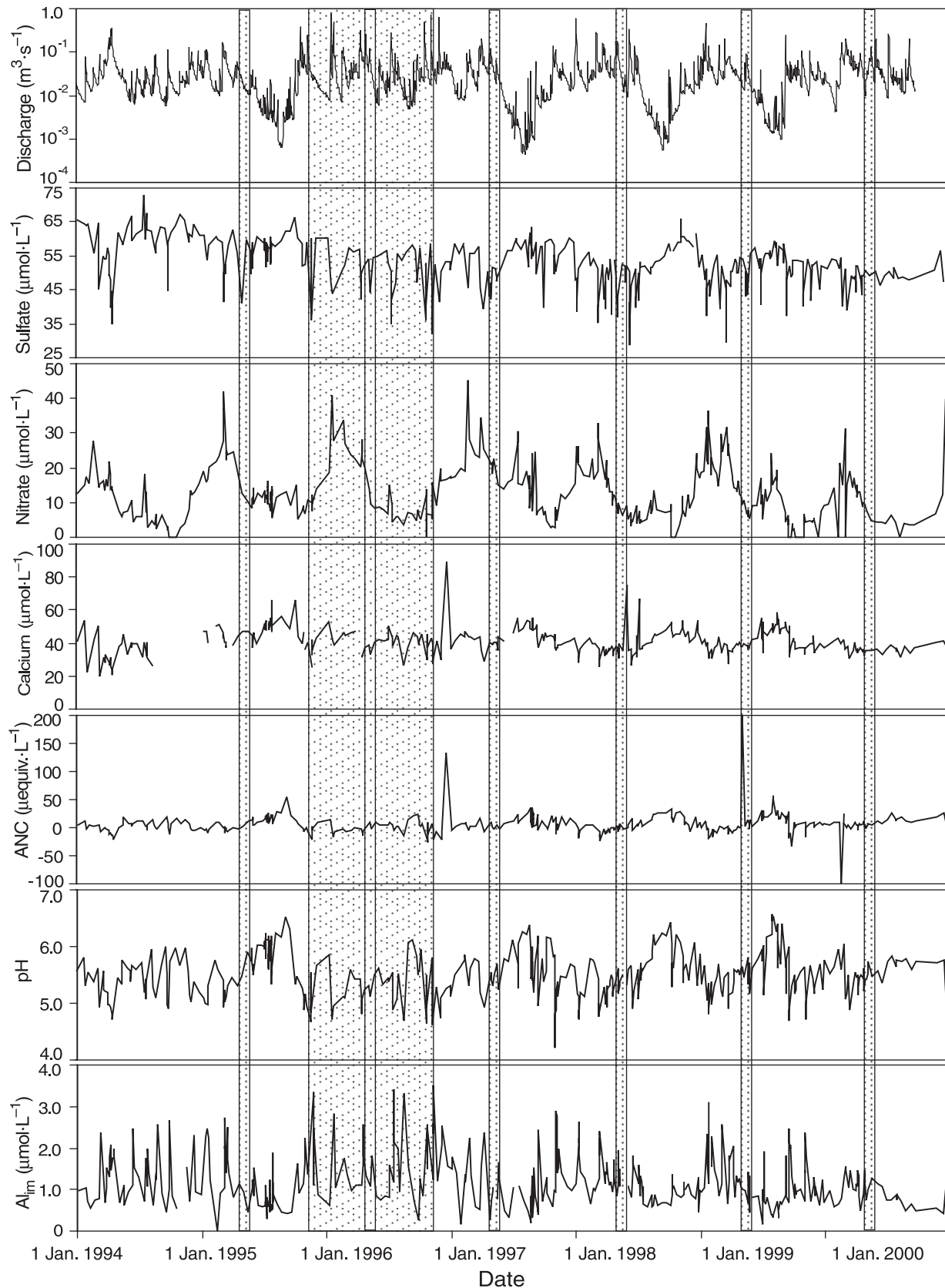


Fig. 5. Daily discharge, acid-neutralizing capacity (ANC), pH, and concentrations of SO_4^{2-} , NO_3^- , Ca^{2+} , and inorganic monomeric aluminum (Al_{im}) for water samples from the reference site (cl25) in the Neversink River basin, New York, 1994–2000. The 30-day brook trout (*Salvelinus fontinalis*) exposure periods are indicated by heavy stippling.

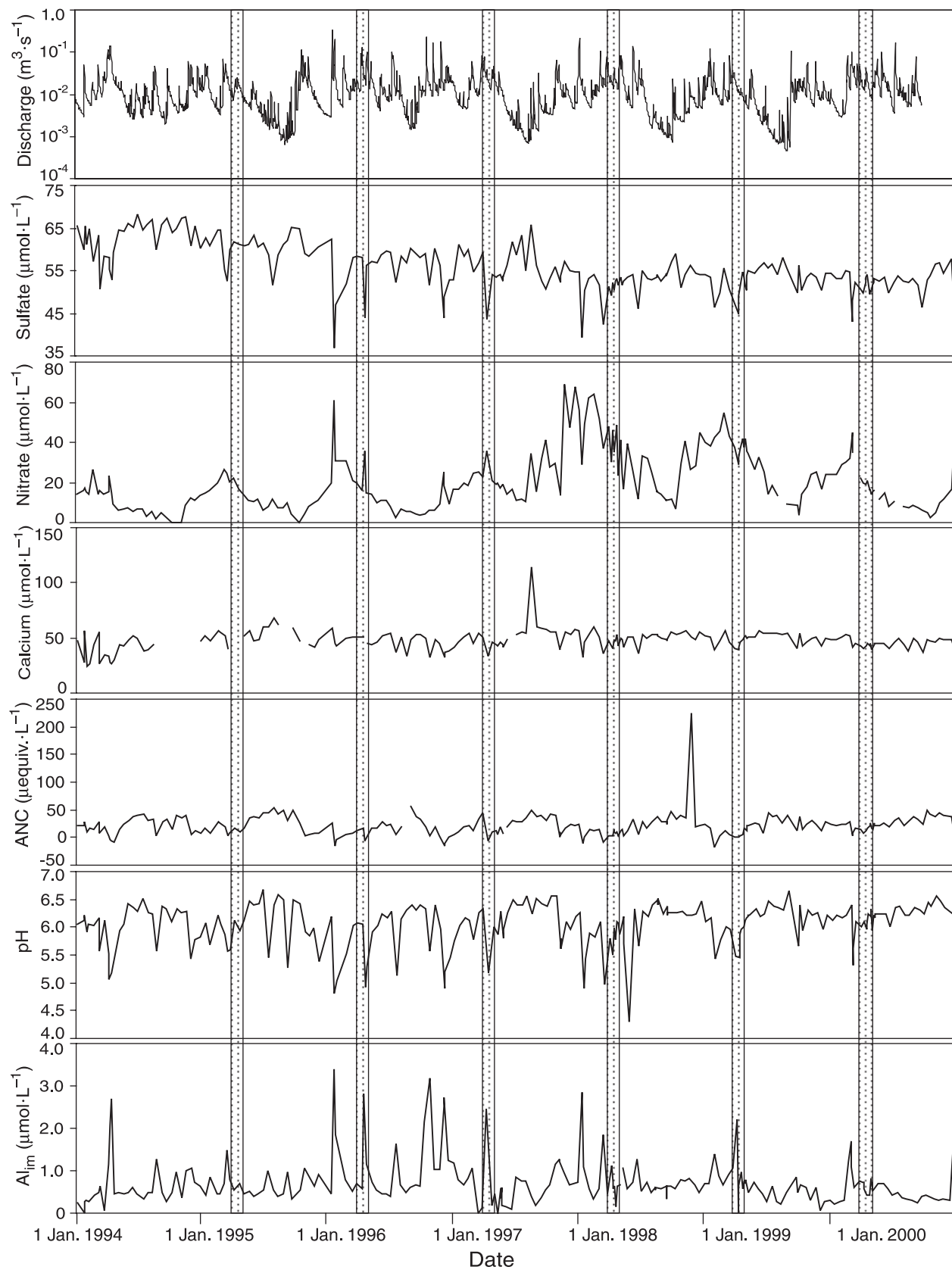
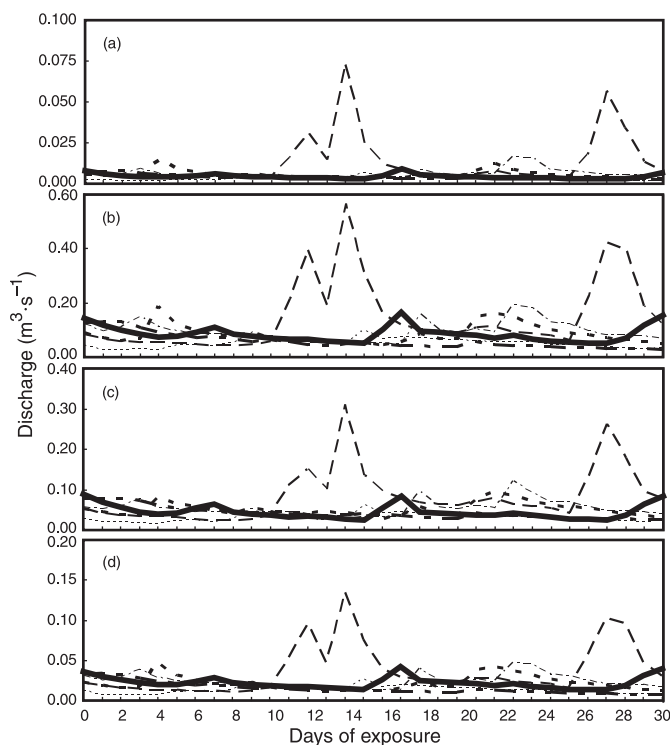


Fig. 6. Hourly discharge at (a) dc57, (b) sc20, (c) sc40, and (d) cl25 during 30-day toxicity tests, spring 1995 (light dotted line), 1996 (medium dashed line), 1997 (light dash-dotted line), 1998 (thick solid line), 1999 (thick dash-dotted line), and 2000 (thick dashed line).



fore, all four streams would be classified as susceptible to acidification and episodically acidic.

Over the 6-year study, NO_3^- concentrations in the reference stream (cl25) showed no long-term trend, but SO_4^{2-} concentrations decreased from a median of $60.9 \mu\text{mol}\cdot\text{L}^{-1}$ in 1994 to $52.4 \mu\text{mol}\cdot\text{L}^{-1}$ in 2000 (Table 1; Fig. 5). Similar long-term SO_4^{2-} declines occurred at dc57 (Table 1) and at sc20 and sc40 (not shown) prior to tree harvests. Several studies also reported SO_4^{2-} declines during the 1980s and 1990s in acidified streams and lakes in eastern North America and Europe (Stoddard et al. 1999; Martin et al. 2000; Driscoll et al. 2003). The decline in the northeastern United States has been associated with decreasing rates of atmospheric SO_4^{2-} deposition in response to decreased S emissions from power-generating facilities as mandated by the Clean Air Act Amendments of 1990 (Lynch et al. 2000; Butler et al. 2001; Stoddard et al. 2003).

Distinct negative effects of tree harvests on water chemistry were evident only at Dry Creek (dc57) in the clearcut subbasin, especially as compared with stable chemistry at cl25 (Table 1; Figs. 2 and 5). Tree harvest occurred during winter 1996–1997, but changes in stream chemistry at dc57 were not obvious until late summer and fall 1997 and corresponded mainly to increasing stream discharge following the first summer growing season. NO_3^- concentrations increased 10-fold from a median of $25.8 \mu\text{mol}\cdot\text{L}^{-1}$ to a median of $259.9 \mu\text{mol}\cdot\text{L}^{-1}$ (peak of $1390.5 \mu\text{mol}\cdot\text{L}^{-1}$) in 1997 (Table 1). Concentrations of Al_{im} also increased from medians of 0.53 and $1.01 \mu\text{mol}\cdot\text{L}^{-1}$ in 1995 and 1996 to a median of $1.81 \mu\text{mol}\cdot\text{L}^{-1}$

in 1998 (Table 1). Al_{im} concentrations increased dramatically during high-flow (storm) events in fall 1997 and spring 1998, reaching a peak of $1390.5 \mu\text{mol}\cdot\text{L}^{-1}$ (Table 1; Fig. 2). While pH ranged as low as 4.65 during high-flow events prior to clear-cutting, pH dropped to 4.32 and 4.42 during several storm events in the first fall (1997) and spring (1998) after tree harvests (Table 1). A twofold increase in stream water concentrations of Ca^{2+} (increased from $48.8 \mu\text{mol}\cdot\text{L}^{-1}$ in 1996 to $111.5 \mu\text{mol}\cdot\text{L}^{-1}$ in 1997) also occurred following tree removal; this increase may have helped prevent larger decreases in pH and ANC than those observed. The observed departures from normal water quality continued through 1999 and much of 2000, but with gradually declining severity.

Decreases in pH and ANC in the clearcut stream post-harvest were related mainly to increased NO_3^- concentrations, not to SO_4^{2-} concentrations. SO_4^{2-} levels decreased from an average of $50\text{--}60 \mu\text{mol}\cdot\text{L}^{-1}$ before and during harvest (1995–1996) to less than $40 \mu\text{mol}\cdot\text{L}^{-1}$ in late 1997. Results from a concurrent study in these subbasins (Welsh et al. 2004) suggest that the decreases in stream water SO_4^{2-} concentrations induced by the clear-cut were possibly caused by increased soil acidification and SO_4^{2-} adsorption. SO_4^{2-} concentrations at the clearcut site, like NO_3^- and Ca^{2+} , returned to near-preharvest levels by late 2000.

In contrast with the marked changes in stream chemistry at dc57, water quality at the TSI site (sc40) did not change following tree harvests, and chemistry at the site below the confluence of Dry Creek and Shelter Creek (sc20) only deviated slightly from normal. The TSI harvest in the upper Shelter Creek subbasin had no discernable effect on surface-water chemistry at sc40 over the long term (Fig. 4) or during the 30-day test periods (Table 2). The lack of water quality changes at the TSI site (sc40) and the major changes in water quality at the clearcut site (dc57) after tree harvests suggest that small changes in water quality at the confluence site (sc20; Fig. 3) were due entirely to the clear-cut harvest in the Dry Creek subbasin. NO_3^- and Ca^{2+} concentrations increased moderately at the confluence site during fall 1997 (NO_3^- and Ca^{2+} peaked at about 110 and $80 \mu\text{mol}\cdot\text{L}^{-1}$, respectively), but pH, ANC, and Al_{im} levels changed little compared with prior years (Fig. 3).

Except for the long-term SO_4^{2-} decline noted earlier, concentrations of most constituents at the reference site (cl25) were relatively stable during base flows and fluctuated normally during high flows from 1994 through 2000 (Table 1; Fig. 5). Concentrations of NO_3^- increased moderately during late 1997, 1998, and 1999 ostensibly because deep soil waters “leaked” from the clearcut watershed across surface-elevation or topographic boundaries into the drainage of the reference stream. The extremely low pH (4.31) observed from one water sample collected at cl25 during the spring of 1998 (Table 1; Fig. 5) does not correspond to a high-flow event and thus may be a misidentified sample. The lack of substantial chemical changes at the reference site (Table 1) and at both TSI sites indicates that other regional trends had little or no effect on the chemistry of waters at the clearcut site during the period of study.

Brook trout mortality

Mortality of caged brook trout before and after the harvests was generally nil or low at all sites except the clearcut

Table 1. Annual median, minimum, and maximum values for selected chemical constituents measured from all routine and storm event samples collected at the clearcut site (dc57) and reference site (cl25), 1995–2000.

	ANC ($\mu\text{equiv}\cdot\text{L}^{-1}$)	Ca^{2+} ($\mu\text{mol}\cdot\text{L}^{-1}$)	DOC ($\mu\text{mol}\cdot\text{L}^{-1}$)	pH	NO_3^- ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{om} ($\mu\text{mol}\cdot\text{L}^{-1}$)	SO_4^{2-} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{im} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{t} ($\mu\text{mol}\cdot\text{L}^{-1}$)
Clearcut site: dc57									
1995, $n = 86$									
Median	59.9	67.9	184.1	6.43	21.0	0.39	57.8	0.53	11.29
Range	–20.2–160.2	37.1–202.6	33.1–780.7	4.72–6.77	6.6–83.1	0–2.71	39.6–64.9	0.21–3.59	4.92–38.24
1996, $n = 75$									
Median	13.3	48.8	175.7	5.86	25.8	1.02	49.4	1.01	11.06
Range	–27.0–70.1	26.5–74.3	59.2–486.2	4.65–6.71	4.5–77.8	0.09–3.70	32.7–61.9	0–5.09	5.38–48.10
1997, $n = 68$									
Median	11.5	111.5	115.1	5.91	259.9	1.06	38.9	1.07	35.76
Range	–71.0–56.4	34.2–226.9	37.1–421.5	4.32–6.56	17.2–1390.5	0–4.57	22.8–62.1	0–86.38	0.66–99.94
1998, $n = 122$									
Median	2.8	93.8	110.5	5.51	227.2	0.10	38.7	1.81	6.88
Range	–95.6–76.6	61.5–153.4	41.1–426.9	4.42–6.50	84.2–570.3	0–3.04	27.9–57.0	0.03–43.97	0.04–61.53
1999, $n = 119$									
Median	20.5	70.6	105.0	6.08	89.3	0.23	46.4	0.74	4.06
Range	–23.0–75.3	35.5–130.6	29.9–682.2	4.66–6.67	0–380.9	0–4.03	33.6–55.5	0–20.89	0.73–31.41
2000, $n = 104$									
Median	26.8	54.8	139.0	6.27	37.9	0.00	52.6	0.66	2.49
Range	–9.7–85.4	29.3–76.6	55.0–566.1	4.77–6.78	0–87.2	0–2.63	38.5–58.9	0.07–3.65	0.63–12.75
Reference site: cl25									
1995, $n = 25$									
Median	26.0	51.8	146.6	6.07	11.1	0.42	60.9	0.55	4.98
Range	2.5–54.7	40.6–668.1	56.3–681.2	5.26–6.67	0–26.4	0–1.19	51.5–65.0	0.33–1.50	3.60–9.40
1996, $n = 27$									
Median	11.6	48.8	129.3	6.03	11.0	0.69	57.0	0.76	8.26
Range	–16.0–57.2	32.3–58.7	66.4–400.3	4.80–6.41	2.5–61.0	0.23–3.12	36.8–62.4	0.39–3.38	3.96–13.68
1997, $n = 31$									
Median	20.9	50.7	129.4	6.18	19.4	0.23	54.8	0.66	2.43
Range	–5.4–49.1	33.4–114.3	75.4–534.0	5.17–6.57	10.7–68.8	0–2.17	43.7–65.9	0–2.46	0.97–8.12
1998, $n = 37$									
Median	16.8	50.2	130.8	6.19	29.6	–0.01	53.2	0.65	2.11
Range	–9.9–224.1	32.7–59.9	80.8–356.8	4.31–6.51	6.6–64.0	0–2.22	39.4–59.1	0.15–2.85	0.96–44.61
1999, $n = 32$									
Median	17.1	49.9	116.7	6.19	28.9	0.21	53.6	0.64	2.22
Range	–17.0–44.0	39.1–57.0	86.7–328.7	5.42–6.65	3.7–55.0	0–1.27	44.9–58.2	0–2.20	1.34–4.25
2000, $n = 35$									
Median	22.8	45.0	121.7	6.22	16.0	–0.18	52.4	0.44	1.64
Range	3.3–49.6	36.8–52.7	86.7–176.6	5.09–6.56	2.6–45.2	0–1.14	42.9–57.8	0.21–1.70	0.76–6.71

Note: ANC, acid-neutralizing capacity; DOC, dissolved organic carbon; Al_{om} , organic monomeric aluminum; Al_{im} , inorganic monomeric aluminum; Al_{t} , total dissolved aluminum; n , the number of samples analyzed.

Table 2. Estimated median, minimum, and maximum values for selected chemical constituents measured at the four sites during 30-day brook trout (*Salvelinus fontinalis*) exposure periods each year from 1995 to 2000.

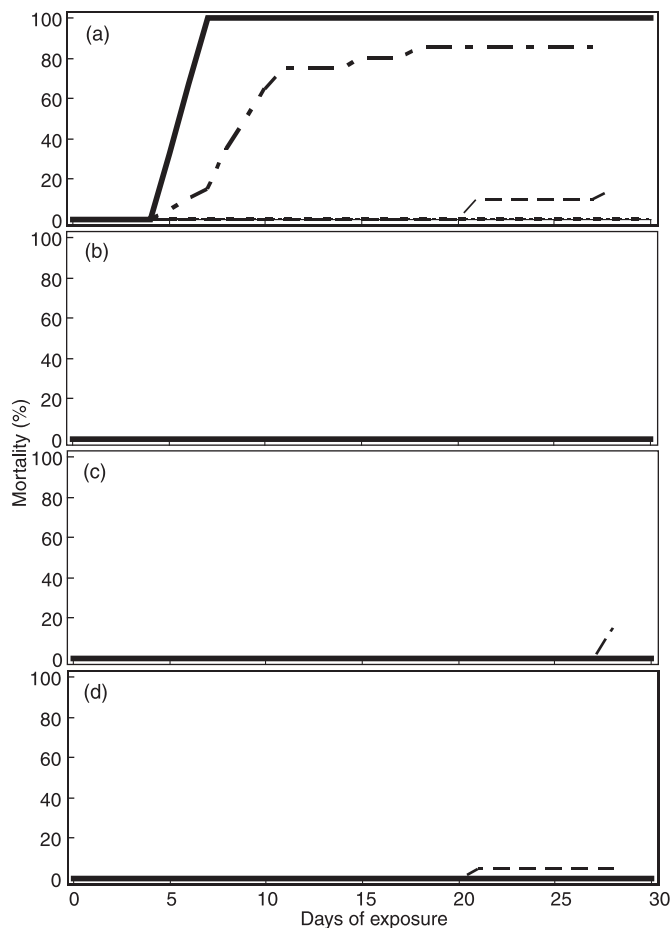
	ANC ($\mu\text{equiv}\cdot\text{L}^{-1}$)	Ca^{2+} ($\mu\text{mol}\cdot\text{L}^{-1}$)	DOC ($\mu\text{mol}\cdot\text{L}^{-1}$)	pH	NO_3^- ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{on} ($\mu\text{mol}\cdot\text{L}^{-1}$)	SO_4^{2-} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{im} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{tm} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_t ($\mu\text{mol}\cdot\text{L}^{-1}$)
Clearcut site: dc57										
1995, $n = 4$										
Median	27.1	61.8	72.5	6.23	28.5	0.05	59.5	0.54	0.59	4.92
Range	10.8–39.6	58.2–65.3	33.1–96.7	5.69–6.36	19.9–34.6	0–0.52	55.7–61.2	0.48–1.49	0.43–2.01	4.92–4.92
1996, $n = 14$										
Median	–13	36.2	218.6	4.87	37.3	1.39	44.6	2.94	4.79	10.14
Range	–21.7–15.7	30.7–59.5	59.2–302.6	4.76–6.28	23.2–47.2	0.28–2.08	41.6–56.7	0.55–5.09	0.83–6.81	7.45–20.2
1997, $n = 7$										
Median	11.3	47.5	138.9	6.05	23.3	1.53	49.3	0.59	1.82	5.73
Range	–2.1–31.2	34.2–54.9	82.7–207.4	5.08–6.39	19.1–31.4	1.11–1.89	45.7–53.8	0.01–3.90	0.85–5.72	2.54–8.91
1998, $n = 15$										
Median	–12.8	100.5	90.6	5.03	263.0	0.26	38.0	4.48	4.61	9.30
Range	–29.5–(–)2.8	79.5–110.7	64.7–181.8	4.64–5.47	220.0–296.3	0–1.11	35.6–40.1	2.02–13.89	2.04–14.84	4.80–21.4
1999, $n = 11$										
Median	3.9	93.6	68.9	5.69	187.9	0	44.1	1.37	1.16	3.90
Range	–21.3–16.7	77.0–122.7	55.3–106.5	5.00–6.21	180.0–203.3	0–0.13	42.3–46.6	0.77–5.92	0.65–5.94	2.23–10.9
2000, $n = 17$										
Median	15.7	56.8	104.3	6.02	54.0	0	53.7	0.82	0.39	2.29
Range	1.9–33.7	43.5–61.8	87.3–205.8	5.14–6.38	38.3–59.9	0–0.23	51.3–57.0	0.43–2.55	–0.06–2.78	1.20–10.9
Confluence site: sc20										
1995, $n = 3$										
Median	12.23	na	136.4	5.63	21.7	0.65	59.9	0.83	1.44	4.84
Range	8.4–13.60	na	133.4–154.3	5.55–5.70	9.7–26.3	0.61–0.70	57.8–60.1	0.75–0.99	1.40–1.69	4.80–5.56
1996, $n = 9$										
Median	2.10	42.8	292.1	5.47	23.1	1.67	49.6	1.08	2.75	na
Range	–4.7–13.2	34.1–50.4	126.0–444.4	5.03–5.72	17.3–33.2	0.79–2.76	39.5–54.3	0.75–2.43	1.61–4.69	na
1997, $n = 7$										
Median	6.80	42.9	235.5	5.82	24.2	2.30	45.6	0.39	3.18	5.96
Range	1.70–12.9	35.0–45.2	118.0–410.6	5.28–6.10	18.9–29.2	1.40–3.41	40.7–51.5	0.17–1.33	1.79–4.74	na
1998, $n = 18$										
Median	5.10	45.7	211.4	5.67	36.9	0.52	49.1	0.99	1.67	4.73
Range	–3.3–18.4	41.6–50.8	128.9–386.5	5.21–5.90	22.0–52.0	0.36–1.84	41.0–53.3	0.41–1.54	0.91–2.85	2.35–17.4
1999, $n = 14$										
Median	8.06	45.1	125.3	5.79	29.1	0.30	51.0	0.88	1.19	3.30
Range	–0.83–14.3	42.7–46.9	110.7–187.0	5.29–6.00	25.7–37.1	0.11–0.71	44.7–55.0	0.30–1.78	0.87–2.04	1.92–4.84
2000, $n = 12$										
Median	11.19	41.1	150.0	5.83	16.3	0.08	50.3	0.78	0.78	3.18
Range	7.67–23.55	38.6–43.5	124.1–365.6	5.20–6.17	13.5–20.8	0–1.47	43.4–52.9	–0.04–1.08	0.52–2.33	2.38–7.67

Table 2 (concluded).

	ANC ($\mu\text{equiv}\cdot\text{L}^{-1}$)	Ca^{2+} ($\mu\text{mol}\cdot\text{L}^{-1}$)	DOC ($\mu\text{mol}\cdot\text{L}^{-1}$)	pH	NO_3^- ($\mu\text{mol}\cdot\text{L}^{-1}$)	SO_4^{2-} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{im} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{tm} ($\mu\text{mol}\cdot\text{L}^{-1}$)	Al_{t} ($\mu\text{mol}\cdot\text{L}^{-1}$)
TSI site: sc40									
1995, $n = 4$									
Median	1.2	45.9	136.9	5.47	15.9	57.8	0.85	1.68	5.56
Range	-2.5–11.9	39.1–47.5	110.7–179.7	5.30–5.91	10.5–24.8	40.9–62.6	0.59–1.02	1.19–2.10	5.15–6.44
1996, $n = 8$									
Median	-4.9	34.6	242.7	5.15	22.5	50.7	1.5	2.97	8.23
Range	-13.5–8.4	31.2–47.2	105.2–326.7	4.82–5.42	13.8–28.3	42.1–56.9	0.72–2.58	1.78–5.16	4.20–10.3
1997, $n = 7$									
Median	0.9	39.9	244.1	5.40	21.6	46.9	2.61	3.60	5.92
Range	-7.3–8.8	28.7–40.9	129.9–412.8	4.93–5.70	18.0–25.3	39.4–51.5	1.56–3.70	1.62–5.44	3.48–8.35
1998, $n = 17$									
Median	-2.9	35.5	209.1	5.30	13.0	48.5	0.85	2.09	5.63
Range	-10–3.5	32.3–37.9	20.7–566.5	4.92–5.62	6.8–22.0	37.8–54.0	0.42–3.18	1.41–4.75	3.30–12.5
1999, $n = 9$									
Median	-0.3	38.2	140.1	5.54	13.8	50.5	0.54	1.61	3.83
Range	-8.7–218.1	35.0–40.1	126.5–183.4	5.20–5.65	9.5–17.3	46.0–54.6	0.28–0.82	1.39–2.76	2.69–7.53
2000, $n = 19$									
Median	4.0	35.5	174.2	5.44	11.6	49.0	0.30	1.35	4.04
Range	-4.3–12.5	32.4–37.2	139.3–366.0	5.14–5.62	7.7–15.1	43.3–52.1	0–1.48	0.83–2.83	2.53–7.78
Reference site: cl25									
1995, $n = 4$									
Median	17.0	54.6	103.3	6.13	15.0	61.1	0.29	0.89	na
Range	10.1–34.4	52.5–56.6	56.3–107.2	5.94–6.46	11.1–21.9	60.9–61.9	0.22–0.78	0.70–1.34	na
1996, $n = 5$									
Median	11.6	47.6	96.9	5.91	16.2	57.1	0.50	1.20	11.02
Range	-6.5–17.2	43.5–51.0	80.6–252.9	4.93–6.07	14.1–35.5	43.8–58.4	0.29–1.84	0.86–4.67	na
1997, $n = 5$									
Median	10.9	44.3	113.7	5.91	19.5	53.8	1.38	1.75	8.12
Range	-5.4–20.0	33.4–46.0	102.5–173.8	5.17–6.29	17.1–35.9	43.7–54.1	1.22–2.17	1.57–4.58	na
1998, $n = 8$									
Median	10.0	48.2	130.1	5.97	37.9	52.0	0.29	0.88	2.51
Range	2.5–14.1	40.9–53.0	93.4–187.7	5.50–6.19	23.4–48.5	49.2–53.3	0.12–0.64	0.72–1.58	1.80–4.03
1999, $n = 9$									
Median	12.5	49.3	104.9	6.12	36.1	51.4	0.04	0.69	2.22
Range	0.4–21.4	39.1–52.4	96.3–158.2	5.46–6.22	28.9–41.8	44.9–54.9	0–0.30	0.06–2.27	1.34–3.58
2000, $n = 9$									
Median	15.8	42.4	121.7	6.16	16.7	51.7	0	0.42	2.05
Range	8.0–26.7	38.7–45.0	107.1–153.0	5.95–6.33	14.2–20.9	49.5–54.0	0–0.03	0.14–0.77	1.56–3.24

Note: ANC, acid-neutralizing capacity; DOC, dissolved organic carbon; Al_{om} , organic monomeric aluminum; Al_{im} , inorganic monomeric aluminum; Al_{tm} , total monomeric aluminum; Al_{t} , total dissolved aluminum; n , the number of samples analyzed; na, not applicable; TSI, timber-stand improvement.

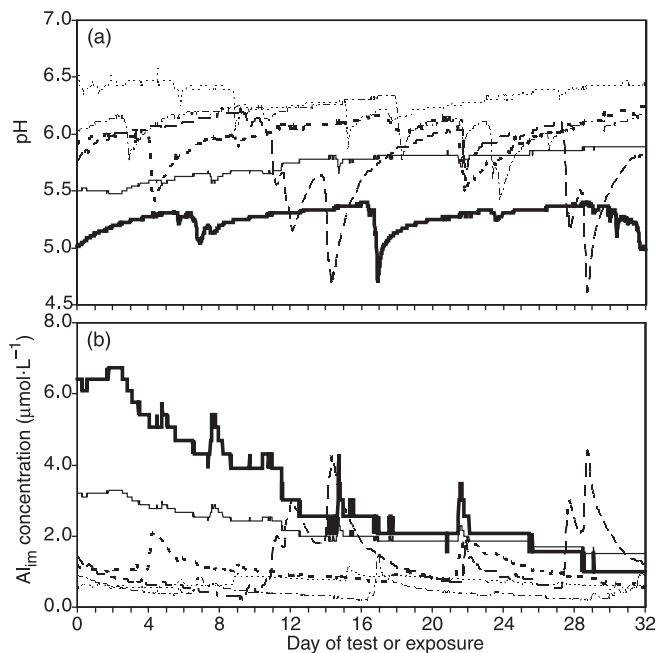
Fig. 7. Brook trout (*Salvelinus fontinalis*) mortality observed during 30-day exposures at (a) dc57, (b) sc20, (c) sc40, and (d) cl25 during toxicity tests, spring 1995 (light dotted line), 1996 (medium dashed line), 1997 (light dash-dotted line), 1998 (thick solid line), 1999 (thick dash-dotted line), and 2000 (thick dashed line).



site (dc57) in 1998 and 1999 (Fig. 7). Trout mortality at dc57 ranged from 0% to 15% before the clear-cut (spring 1995 and 1996) and during the first exposure period after the clear-cut (spring 1997). All (100%) caged brook trout died during the first 7 days of the spring 1998 test at dc57 and 85% died during 30 days of exposure in spring 1999. None (0%) died during the 30-day exposure in 2000. Bioassays were not conducted during fall high-flow periods at any site; however, chemistry data from dc57 (Fig. 2) strongly indicate that water toxicity and trout mortality rates in fall 1997 would have been greater than those observed during spring 1998. No precise tree harvest threshold for trout mortality could be defined from our results, but the 14% reduction in tree BA at the TSI site (sc40) caused no mortality, while the 73% reduction in tree BA produced 100% mortality at the clearcut site (dc57).

Increased trout mortality in acidified streams of the northeastern United States is generally induced by elevated Al_{im} concentrations or some combination of acid and Al_{im} toxicity (Baker et al. 1990; Baker and Christensen 1991). Previous studies of episodic acidification and toxicity in New York and Pennsylvania streams determined that mean or me-

Fig. 8. Estimated hourly (a) pH and (b) inorganic monomeric aluminum (Al_{im}) concentrations at dc57 during 30-day brook trout (*Salvelinus fontinalis*) exposure periods, spring 1995 (light dotted line), 1996 (medium dashed line), 1997 (light dash-dotted line), 1998 (thick solid line), 1999 (thin solid line), and 2000 (thick dashed line).



dian Al_{im} or Al_{t} concentration, or a combined duration and Al_{im} concentration factor, consistently explained the greatest amount of variability in mortality of native brook trout (Gagen et al. 1993; Simonin et al. 1993; Baldigo and Murdoch 1997). Acid- Al_{im} episodes in the Neversink River basin were found to cause significant mortality in native brook trout when Al_{im} levels exceeded $0.200 \text{ mg}\cdot\text{L}^{-1}$ ($7.4 \text{ }\mu\text{mol}\cdot\text{L}^{-1}$) for 2 or more days and that several constituents, including pH, DOC, Ca^{2+} , and Cl^{-} , were also significantly correlated with brook trout mortality (Baldigo and Murdoch 1997). A concurrent study in several acidic streams of Pennsylvania found that ionoregulation of native brook trout failed, and mortality occurred, when Al_{t} concentrations reached $0.2\text{--}0.3 \text{ mg}\cdot\text{L}^{-1}$ ($7.4\text{--}11.1 \text{ }\mu\text{mol}\cdot\text{L}^{-1}$) and exposure durations were longer than 1.5 days; more than 90% of Al_{t} was typically in the reactive inorganic form (Gagen and Sharpe 1987a, 1987b). A third concurrent investigation in four streams of the western Adirondack Mountains of New York found that an Al_{im} concentration of $0.1 \text{ mg}\cdot\text{L}^{-1}$ ($3.7 \text{ }\mu\text{mol}\cdot\text{L}^{-1}$) was the threshold for mortality of native brook trout during acid- Al_{im} episodes (Simonin et al. 1993). Other field and laboratory studies documented significant mortality of native and hatchery-raised brook trout when concentrations of Al_{im} and (or) Al_{t} exceed either 0.200 or $0.300 \text{ mg}\cdot\text{L}^{-1}$ under low Ca ($<2.0 \text{ mg}\cdot\text{L}^{-1}$), DOC ($<2.0 \text{ mg}\cdot\text{L}^{-1}$), and pH (4.4–5.2) conditions (Baker et al. 1990; Van Sickle et al. 1996). These findings demonstrate that Al_{im} can be acutely toxic to juvenile brook trout in waters of the northeastern United States when concentrations reach $3.7\text{--}7.4 \text{ }\mu\text{mol}\cdot\text{L}^{-1}$.

Estimates of continuous (hourly) pH and Al_{im} data (Fig. 8) and from samples collected during the 30-day exposure periods each year (Table 2) at dc57 confirm that the clear-cut affects water chemistry and indicate that the toxic Al_{im} threshold may be somewhat lower for hatchery brook trout used in the present investigation than for native brook trout used in other studies. Although estimated Al_{im} records are somewhat subdued, they depict concentrations well above $3.7 \mu\text{mol}\cdot\text{L}^{-1}$ during the first 7 days during the 1998 tests where all trout died, levels near $3.7 \mu\text{mol}\cdot\text{L}^{-1}$ for several days in 1999 where 85% died, and short excursions in excess of $3.7 \mu\text{mol}\cdot\text{L}^{-1}$ in 1996 where 15% died (Fig. 8b). Few or no trout died during the tests done in 1995, 1997, and 2000 where Al_{im} concentrations did not exceed $3.0 \mu\text{mol}\cdot\text{L}^{-1}$. Data from samples collected during test periods show that Al_{im} concentrations at the clearcut site did not surpass $3.9 \mu\text{mol}\cdot\text{L}^{-1}$ during exposure periods in 1995, 1997, and 2000 but reached a maximum of $13.9 \mu\text{mol}\cdot\text{L}^{-1}$ during the 1998 test, $5.9 \mu\text{mol}\cdot\text{L}^{-1}$ during the 1999 test, and $3.9 \mu\text{mol}\cdot\text{L}^{-1}$ during the 1996 test (Table 2). Thus, the high rates of mortality during the springs of 1998 and 1999 could be attributable to Al_{im} concentrations that exceeded brook trout thresholds for survival that range near $3.7 \mu\text{mol}\cdot\text{L}^{-1}$. The death of all brook trout at the clearcut site during the first 7 days of the 1998 test was attributed to persistent acute toxicity, possibly intensified by a storm flow that occurred shortly before the test began. Maximum concentrations of Al_{im} at the other three sites did not exceed $2.9 \mu\text{mol}\cdot\text{L}^{-1}$ during any 30-day test period or at the clearcut site during 1995 and 2000 (Table 2). The low level of trout mortality (15%) at the clearcut site (dc57) during 1996 was possibly related to two or three consecutive high flows that produced strong acidification (minimum pH 4.8) along with the highest Al_{im} concentration ($5.09 \mu\text{mol}\cdot\text{L}^{-1}$) observed at any of the sites before tree harvests. Thus, stream water concentrations of Al_{im} may have approached and surpassed thresholds toxic to brook trout. The low levels of brook trout mortality during spring 1996 at the TSI (15%) and reference (5%) sites, however, do not appear to be related to high Al_{im} concentrations.

The increase in Al_{im} concentration and mortality of brook trout at the clearcut site after the harvest appear to have been caused by decreases in N uptake by vegetation and increased nitrification, NO_3^- , and acidity in soil and surface waters throughout affected parts of the subbasin (Burns and Murdoch 2005). These changes, in turn, can increase mineral-Al solubility in affected soils and consequently elevate Al_{im} concentrations in receiving streams. An analysis of Catskill stream chemistry data through a simple chemistry equilibrium model, ALCHEMI (Schecher and Driscoll 1987), indicates that Al concentrations are consistent with control by an aluminum hydroxide solid phase similar to gibbsite, $\text{Al}(\text{OH})_3$. Water pH controls the dissolution of the aluminum hydroxide solid and, therefore, Al speciation and Al_{im} concentrations (Driscoll 1985). Dissolution of gibbsite and the aluminum hydroxide solid increases at pH levels above and below 6.0; thus, decreases in water pH below 6.0 typically cause the concentration of inorganic Al species to increase (Driscoll 1985). The high rates of brook trout mortality in waters of the clearcut watershed, therefore, can be attributed to sequential alterations in normal hydrogeochemical processes that occurred as a result of tree harvest. The low rates

of trout mortality at the TSI (sc40) and confluence (sc20) sites after removal of 5% and 14% of tree biomass in their respective subbasins indicate that these levels of biomass removal were not sufficient to strongly affect Al_{im} mobilization and produce water toxicity.

Brook trout are relatively tolerant of acidic conditions compared with many other stream-dwelling fish species (Baker and Christensen 1991). Several studies in New York and Pennsylvania streams have demonstrated that slimy sculpin (*Cottus cognatus*), mottled sculpin (*Cottus bairdi*), and blacknose dace (*Rhinichthys atratulus*), species that co-inhabit small streams with brook trout, almost always experienced higher levels of mortality than juvenile brook trout when exposed to toxic acid- Al_{im} conditions during in situ bioassays (Johnson et al. 1987; Gagen et al. 1993; Simonin et al. 1993). This is corroborated by fish species distributions throughout the upper Neversink River basin (Baldigo and Lawrence 2001). These authors found that no fish species occurred in the most toxic headwater reaches and brook trout alone extended farthest into headwater reaches with very low pH and high Al_{im} concentrations; additional fish species accrued in community assemblages farther downstream as pH increased and Al_{im} decreased. The sequence of community additions could be predicted from species acid- Al_{im} tolerance levels derived from in situ bioassays: slimy sculpin were the next most tolerant species and added first followed by brown trout (*Salmo trutta*), longnose dace (*Rhinichthys cataractae*), blacknose dace, and Atlantic salmon (*Salmo salar*) (Baldigo and Lawrence 2001). Although no other fish species were observed in the Shelter Creek study reaches, the acutely toxic conditions after the clear-cut in Dry Creek would probably have killed all other resident fish species if any had been present. Thus, the brook trout mortality reported herein may underestimate the potential implications of acidification induced by the clearcut for other fish species. The likelihood that local clear-cutting harvests across other parts of eastern North America could adversely affect resident fish species and fish communities cannot be determined from our results, but may be substantial, considering the tolerance of brook trout to Al_{im} and acidity and the extent of tree harvests within high-elevation watersheds containing small headwater streams.

In summary, the combined effects of clear-cut harvest and acid deposition on water quality of small streams in the Catskill Mountain region can produce severe stream acidification and conditions that are acutely toxic to juvenile brook trout. Clear-cutting may not be the universal logging practice in the region, but our results indicate that it nevertheless can adversely affect the chemistry of circumneutral and acidified streams in the Catskill region. Partial or TSI harvests in subbasins with few acid-sensitive streams would probably not adversely affect surface-water chemistry or harm resident brook trout populations if the harvests were limited to the extent and intensity applied in this study. Populations of other acid-sensitive fish species and of entire aquatic ecosystems are more susceptible than brook trout to the effects of episodic acidification and thus to any practice that could increase the magnitude, duration, or frequency of acid- Al_{im} episodes in poorly buffered streams. Therefore, decisions as to the type, extent, and intensity of timber harvests in some watersheds may warrant consideration of the status of soil

acidity, the susceptibility of stream waters to acidification, and the sensitivity of resident biota to acid- Al_{im} episodes. The forest harvest thresholds that adversely affect survival of brook trout and other fish species in acidified streams of the Catskill Mountain region and other parts of eastern North America remain to be defined through additional research.

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